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Factors That Support Teacher Shift to Engineering Design

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Abstract

This paper presents a professional development (PD) program conducted at the University of Cincinnati for middle school and high science and math teachers. Teachers commit to the National Science Foundation (DUE-1102990) funded Cincinnati Engineering Enhanced Science and Math Program (CEEMS) for two years and learn to transform their classrooms into places where students collaboratively tackle real world, open-ended challenges by using the engineering design process. This paper focuses on three important elements of the PD that prepares teachers to incorporate engineering design process into the teaching of core science and math content. First, teachers experience engineering challenges themselves. By engaging in teamwork and collaboration, learning from failure, and experiencing the iterative nature of the engineering design process for themselves, teachers better identify with students. Second, the PD program is structured such that teachers are accountable to create and implement engineering design activities in their classrooms. Finally, teachers are supported and guided as they create and implement engineering design modules. This is accomplished using resource coaches, engineers and master teachers, who guide the teachers through the process of creating and implementing lessons incorporating engineering design activities and provide invaluable feedback as teachers reflect on their own practice. Program evaluation focuses on teacher changes in instructional practices, student growth in content knowledge, and student engagement. Related evaluation results and teacher feedback are documented. As indicated by teacher self-report current instructional practices, teachers' shift in practices to a student-centered, engineering design-based approach seems to support students' growth in content knowledge as measured by pre-post assessment results. Beyond effective content delivery, student engagement in engineering design challenges is high, as indicated by teacher qualitative data.

Introduction

As the Next Generation Science Standards[12] emphasizes the importance of students utilizing science and engineering practices, educators need to learn to shift their instructional practices from teacher-centered "stand and deliver" lectures and "cookie cutter" labs to student-directed engineering design challenges. The University of Cincinnati received a National Science Foundation grant to develop a Targeted Math and Science Partnership. The Cincinnati Engineering Enhanced Science and Math Program (CEEMS) has worked with local middle school and high school teachers from select fourteen school districts over two years to transform their classrooms into places where students collaboratively tackle real world, open-ended challenges by using the engineering design process.

This paper will focus on three important factors to be included in professional development that prepares teachers to incorporate the engineering design process into the teaching of core science content. First, teachers need to experience engineering challenges themselves. By engaging in teamwork and collaboration, learning from failure, and experiencing the iterative nature of the design process for themselves, teachers can better identify with students as the learning occurs. Second, professional development programs must be structured such that teachers are accountable to create and implement engineering design activities in their classrooms. It is not enough to sit in a workshop and listen to what others have done; teachers need to try engineering design in their own classrooms and experience the benefits over time as they refine those activities. Finally, teachers need support and guidance as they create and implement engineering design challenge modules. The key to the program's success are resource coaches, engineers and master teachers, who guide the teachers through the process of creating and implementing lessons incorporating engineering design activities and provide invaluable feedback as teachers reflect on their own practice.

Program evaluation focuses on teacher change in instructional practices, student growth in content knowledge, and student engagement. By participating in engineering courses and pedagogy workshops, creating and implementing modules incorporating engineering design challenges unique to their course content, and receiving continual support and guidance from a resource team of engineers and master educators, teachers report significant changes in their instructional practices over their two-year stint in the program. Teachers complete an instructional practices survey prior to program participation, at the program's mid-point, and at the end of their two-year commitment. The survey measures the extent to which teachers incorporate key instructional practices associated with engineering design-based learning as well as their level of confidence in implementing those same practices. Results from a paired-sample, two-tailed, t-test analysis indicate that there were statistically significant increases in the initial two cohorts' reported levels of confidence for all current instructional practices listed between the start-of-the-project and mid-project.

In addition, teachers' shift in practices to a student-centered, engineering design-based approach seems to support students' growth in content knowledge. Included in each engineering design challenge module created by teacher participants is a content-based pre- and post-assessment. A paired-samples two-tailed t-test was conducted to compare students' content knowledge at the beginning and end of the curricular units. Results indicate that 70 out of 76 units had a significant increase in assessment test scores from the pre-test to the post-test at a 95% confidence interval. Beyond effective content delivery, student engagement in engineering design challenges is high, as indicated by teacher qualitative data.

Literature review

The Next Generation Science Standards[12] and the Ohio New Standards for Science[13] both place a high value on teachers integrating engineering design into the science classroom. In addition, while the Common Core Standards[2] do not specifically mention engineering design, the math practices coincide well with engineering activities focused on math content. Yet, as the

National Academy of Engineering[11] suggests, few teachers are comfortable in integrating engineering design with science or math content.

With an increasing expectation that teachers incorporate engineering design into content courses, professional development is necessary.[8] Effective professional development involves the key factors of substantial time investment, systemic support, and opportunities for active learning.[3] Heck et al. further emphasize the importance of time investment, as their research on teacher professional development indicates that teachers' use of innovation was greatest in the first 80 hours of interaction and then leveled off, but after 160 hours, innovation increased again.[9] This seems to suggest that a one or two day workshop on incorporating engineering design will not be enough to transform teachers' practices. Likewise, Guskey identifies the two highest levels of evaluation of professional development as teacher participants' use of new knowledge and skills and impact on student learning outcomes.[7]

Training teachers to utilize the engineering design process as a pedagogy holds promise because design-based learning has demonstrated some success in student acquisition of content.[4] In at least one study, a design-based approach to teaching science content seems to out-perform a scripted inquiry approach, especially among low-achieving African Americans.[10] Learning science via engineering design also seems to facilitate the transfer of the same skills and content to other real world contexts.[4] In Guskey's model for professional development, teachers need to see student results before fully embracing new instructional practices.[7] As a result, teachers will more likely incorporate engineering design in their classrooms if they see evidence of enhanced student learning. The theory of change that guided this project is presented in **Figure 1**.

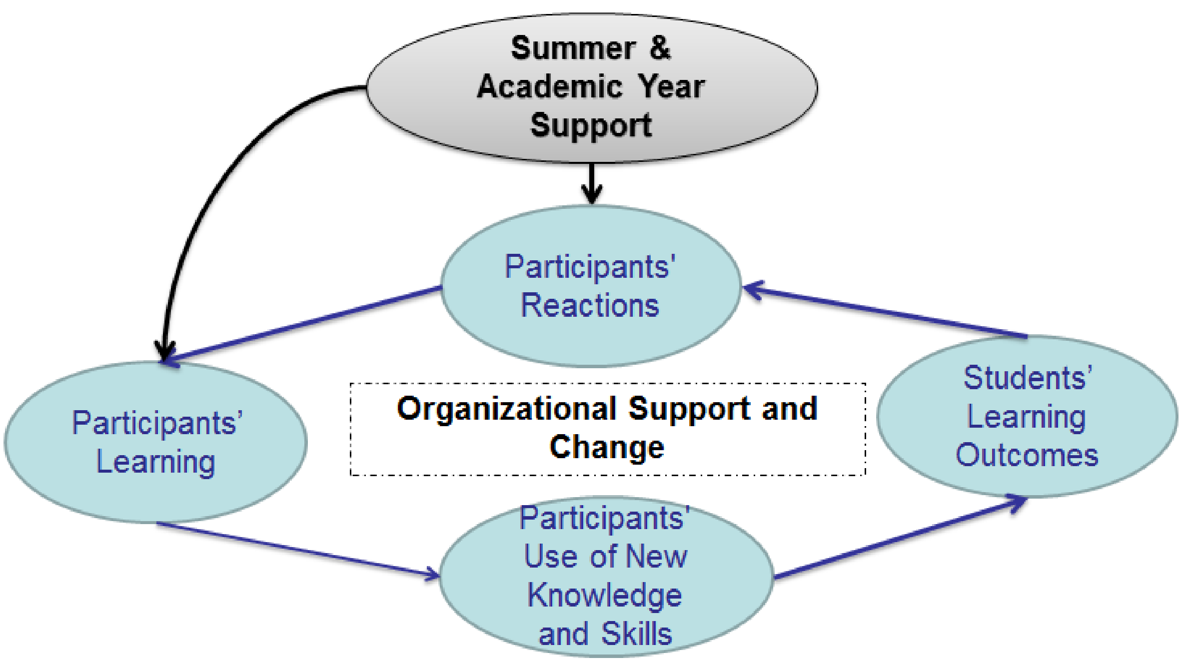


Figure 1: Theory of Change Guiding CEEMS Project

Other organizations have studied the impact of providing professional development to teachers who are tasked with incorporating engineering design in their content courses. For example, the Minnesota Department of Education provided professional development in engineering education to teachers via several regional Mathematics and Science Teacher Partnerships. Researchers coded and analyzed the lessons created by 3^{rd}-6^{th} grade teachers in 2010-11 after completing professional development geared to incorporating engineering design in their content classes.[7] The Science Learning through Engineering Design (SLED) project also worked with teachers in similar grade levels to train them in the engineering design process and collaborated with them to design and implement engineering activities for the classroom. Case studies revealed that the SLED professional development provided the teachers with high level understandings of the engineering design process prior to implementation. The teachers were able to develop engineering activities, but classroom implementation of these activities did not necessarily reflect the same high levels of understanding.[1]

Key questions

This program trains secondary teachers in engineering design pedagogy. Evaluation data focuses on both teacher change in instructional strategies and student outcomes. Key questions include:

1. Did the professional development program result in a shift in teachers' instructional practices?
2. If so, what key factors contribute to a successful professional development program for teachers who are tasked with integrating engineering design challenges into their teaching?
3. When teachers shift from teacher-centered pedagogy to a design- and challenge-based, student-centered approach, do students still grasp the necessary science and math content?

CEEMS professional development structure

Teachers from 14 partner school districts have voluntarily agreed to participate in a two-year program focusing on integrating the engineering design process into their classrooms. Teachers have to apply and be selected to participate in the CEEMS program. In order to apply, they needed to teach science, math, technology, or engineering at the middle school or high school level and teach in one of the program's 14 partner school districts. Approximately 20 new teachers are selected to a new cohort each year, based on district recommendations and a screening process designed to identify if the program is a good fit for applicants. This paper focuses on the first two cohorts of teachers participating in CEEMS. Cohort 1 teachers started the program in June 2012 and completed the program in May 2014. Cohort 2 teachers began CEEMS in June 2013 and will complete their requirements in May 2015.

The teaching method to integrate the engineering design process in math and science content is the challenge-based learning pedagogy, which is very student-centric. Within a challenge-based environment, students learn specific content as they solve engineering design challenges. Scaffolding structures guide student progress through the challenge.[14, 15] Challenge-based environments can mimic design or provide motivating reasons for students to solve problems to address a societal issue and in the process learn science and math content.

In the challenge-based learning pedagogical approach, student groups, under a teacher's guidance, solve real world issues using technology and a hands-on approach. Grounded in student learning outcomes defined using academic standards selected for a unit, students begin with a relevant "big idea." This is an item of global, regional or local significance – something a student can readily relate to his or her life. Once the big idea is selected, the first step is to collaboratively develop - with the students - an overview of the big idea and the related "essential questions" and choose one that sets the broader context and foundation for the work that will follow. The class then identifies a suitable "challenge" or is introduced to the challenge. This establishes the context for the "engineering design challenge" selected for the unit. The students then begin the process of identifying the "guiding questions" that will guide their analysis of the engineering design challenge topic. These questions outline what the students think they need to know to formulate a viable solution. Students need significant guidance from the teacher depending on the particular engineering design challenge selected for the unit and student preparation. This is where content knowledge requirements can be established. Student teams seek to find answers to the guiding questions by participating in a variety of learning activities, conducting research, learning new material (independently, in groups or as part of an instructor-led lesson), experimentation, interviewing, and exploring various avenues to assist in crafting the best solution for the engineering design challenge. The engineering design process (EDP) guides and informs the solution of the challenge. Because there are constraints, trade-offs, and performance objectives there will typically be a variety of potential solutions. Thus, the engineering design process is an iterative process that requires the design's revision and optimization. Using knowledge gained (through the guiding questions and activities) and knowledge experiences they bring with them to the class, students identify the best alternative and implement and defend their best unique solution as a culminating activity.

Participants in both cohorts spent two summers taking a total of six graduate level courses (three courses each summer) where faculty instructors model the integration of engineering design challenges into math and science content. These classes provide participants with the opportunity to practice engineering design themselves, thus allowing them to experience teamwork and collaboration, learn from failure, and encounter the iterative and cyclic nature of the re-design process. In addition to the coursework, the summer program also consists of workshops related to classroom teaching pedagogies, instructional strategies, formative and summative assessment methods, and tips for designing and implementing engineering design challenge activities into the classroom.

Alongside the completion of summer coursework, teachers are expected to fully develop five instructional units which will be implemented in their classrooms over the course of two school years. Each unit typically consists of, but not limited to, two lessons, and each lesson typically consists of two or more activities. An activity is a stand-alone curricular entity, designed to answer one or more of the guiding questions framed for the unit, which are mapped to specific standards. One or more of the activities is formulated to solve, revise and defend the challenge using the engineering design process. Depending on the contents covered in the individual activities, they are grouped into topical areas designated by the lesson titles. For example, Lesson 1 could include activities that teach the content needed to solve the engineering design challenge. Lesson 2 could be hands-on activities conducted to find the optimized "best" solution to the engineering design challenge. Each year a teacher develops and teaches three such units, which include one unit taught in the first year that is revised, re-taught and assessed in the second year. Thus, in total, each teacher develops and executes five unique units during their two year participation in the program. These units are not developed in isolation, as each teacher is assigned to two resource team coaches and, in their first year in the program, a doctoral student in engineering, called a Fellow.

We borrow the tested *Clinical Model*[16] from teaching hospitals, where practitioners, clinical professors, and researchers work together to improve services to patients and prepare future practitioners. In the project, an experienced resource team, consisting of three retired engineers and seven education specialists, takes on this role. While the whole 10 members of the resource team were collectively available to all the teachers, each teacher was assigned to two resource team coaches. Generally, one was an engineer and another was a seasoned educator. In addition, teachers in their first year of the program were assigned a third member of the team—a Fellow, an engineering doctoral student who has expressed an interest in pursuing an academic career upon graduation and has participated in a Preparing Future Faculty (PFF) program that includes a course on teaching and assessment methods, classroom dynamics, and all aspects of a future faculty career. The program builds on this course by also providing workshops to learn more about students learning, communication skills and teaching in an apprenticeship environment designed so that Fellows learn from educators (participating teachers) as the Fellows provide them support in engineering content, design practices and career choices.

The resource team coaches consist of experienced educators and engineers; most are retired. This support system is integral in unit development. In fact, the primary resource coach for each teacher must "sign off" on each unit prior to it being considered completed and ready for teaching. A standard template for a unit and activity is made available to a teacher, which is used by the resource team coach to check compliance of completion of the required elements of a unit prior to teaching. The same support team observes and provides assistance during the implementation of all three units. The primary coach meets with the teacher after each unit is complete to de-brief and discuss ways to improve the next unit's implementation. In addition to these professionals, the engineering doctoral students or Fellows trained in the pedagogies used in the project visit the teachers on a regular basis to support them implementing their units. After a unit has been taught, a teacher adds pre- and post-test results, methods used to address misconceptions and differentiation when teaching the unit, and reflections on what worked and what changes are recommended, if any. The final unit template is again reviewed and approved by the primary resource coach. One member of the project team does the final checking of each unit prior to web dissemination.

Changes in teachers' instructional practices

To measure changes in teacher instructional practices and behaviors in the classroom, an overall survey was developed that documents participating in-service teachers' current instructional practices that are associated with challenge based learning and the engineering design process. The Current Instructional Practices survey measures self-reported changes in the instructional practices of the Summer Institute for Teachers (SIT) participants. The survey has two batteries of 15 questions listing the same challenge-based/design-based learning practices. One battery of questions asks about participants' incorporation of these practices into instruction and the second battery of questions asks participants to indicate their level of confidence when using these instructional practices. Teachers complete the survey prior to starting the program, at the program's mid-point (beginning of second summer in program), and at the end of their two-year commitment.

In May 2014, a factor analysis was conducted on the survey and four factors were identified using data collected from both cohorts during the project orientation meeting prior to the beginning the program. The first factor is the entire survey and we are calling it "Overall - Engineering Design Process (EDP)." The second factor consists of the practices that start with the word "Provide" and relate specifically to the engineering design process implementation. This factor remains stable through all administrations of the survey. The other two factors are harder to identify but one consists of the statements starting with "Guide" and are related to the teacher guiding the implementation of the engineering design challenge process in the classroom. The last factor consists of the statements that contain "Connect" and are related to the teachers discussing application, careers, and societal impacts (ACS) when teaching these units with real world connections. The "Provide" factor is the initial factor that should change as a result of professional development because these statements relate to teacher-centric behaviors. The "Guide" factor typically develops more slowly because it is related to intentionally changing one's practices to more student-centered instructional approaches. The final factor, "Connect," has the teachers incorporating information specifically related to the real world applications and careers into their units. This last factor does not include EDP and will not be included in this paper. See **Table 1** for list of questions used in the Current Instructional Practices survey and their mapping to the different attributes described above.

Reliability of the scale used on the surveys was analyzed using Cronbach's Alpha statistic. When interpreting Cronbach's Alpha, the closer the coefficient is to 1.0, the greater the internal consistency of the items in the scale. In other words, the scale is more likely to be measuring one construct of one or more factors but they are internally consistent.[6] George and Mallory[5] provide the following rules of thumb: "$\alpha > 0.9$ – Excellent, $\alpha > 0.8$ – Good, $\alpha > 0.7$ – Acceptable, $\alpha > 0.6$ – Questionable, $\alpha > 0.5$ – Poor, and $\alpha < 0.5$ – Unacceptable" (p.231). When scale reliability was determined for all administrations of the surveys, it indicated a good to excellent level of reliability for the entire group of usage statements (Cronbach Alpha = 0.849, 0.801, and 0.837, for the start, mid-project and post-project survey administrations, respectively) and the usage survey questions that are included in the "Provide" factor (Cronbach Alpha = 0.835, 0.827, and 0.863, for the start, mid-project and post-project survey administrations, respectively). Overall, the "Guide" factor usage statements scale reliability was though acceptable at the start of the project (Cronbach Alpha = 0.723); then, decreased to very low levels in the mid-project and post project survey administrations (Cronbach Alpha = 0.363 and 0.387, respectively). The sample size for the analysis was 34 for participating teachers in Cohorts 1 and 2. As the number of teachers involved in the project increased, the reliability of the results for these factors also increased. This is an area for further investigation and verification and will be discussed in future publication. By contrast, overall survey and statements related to all factors had acceptable reliability scores for the Confidence questions. A summary of Cronbach's Alpha statistics values obtained for the factors considered for the Current Instructional Practices survey data collected at the start (pre), mid and end (post) points for all teachers are shown in **Table 2**.

For all participating teachers in both cohorts, results from a paired-samples (two-tailed) t-test statistical analysis to compare their changes in instructional practices from the beginning of the project to one year into the project indicate that there were significant increases, at the 95% confidence level, in participants' reported levels of usage and confidence for all current instructional practices listed.

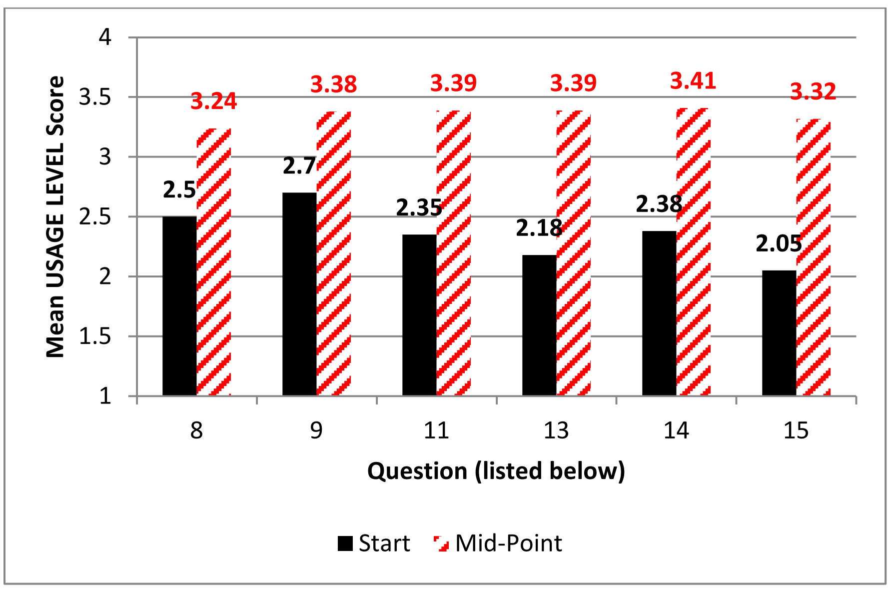
Usage results from for questions in **Table 1** connected with EDP are presented in **Figure 2** for all participating teachers. The scale for these questions was: 1=Never Use; 2=Have Tried It; 3=Use Occasionally; 4=Use Regularly. While this is not a continuous scale, the categories are ordinal with regard to our desired increase levels defined as 2 = better than 1, 3 -= better than 2, and 4 = better than 3. As can be seen from **Figure 2**, teachers reported significantly higher levels of usage for all these practices at the mid-project point compared to the start of the project. Additionally, all starting means were below 3 out of 4 indicating that, as a group, the teachers used these practices only occasionally or had simply tried them. After one year in the project, these same teachers (both cohorts) increased their usage levels of these practices so that they were using them at least regularly. When distributions of responses are reviewed, all of these practices were used which was not the case at the beginning of the project. This is an accomplishment as it indicates that the project is having a positive impact on teacher's instructional behaviors.

Table 1: Factors within Current Instructional Practices Survey

Question	Overall	Provide	Guide	Connect
1. Explicitly connect class content to complex problems or issues with global impact	X			X
2. Explicitly connect class content to real world examples and applications	X			X
3. Explicitly connect these real-world applications to STEM careers	X			X
4. Explicitly connect class content to how people in STEM careers use their knowledge to address societal impacts	X			X
5. Guide students to break complex global problems in to their local and more actionable components	X		X	
6. Guide students in refining problems	X		X	
7. Guide students in planning investigations to better understand different components of problems	X		X	
8. Provide opportunities for students to gather information about problems or issues of importance	X	X		
9. Provide students with opportunities to explore multiple solution pathways for problems	X	X		
10. Guide students in weighing the pros and cons of different solution pathways	X		X	
11. Provide opportunities for students to test their solution pathways	X	X		
12. Guide students in evaluating the results of their solution pathways	X		X	
13. Provide students with opportunities to refine and retry a solution pathway	X	X		
14. Provide opportunities for students to communicate their solution pathways and results to others	X	X		
15. Provide opportunities for students to take responsibility for the decisions they made about the processes used in solving complex problems	X	X		

Table 2: Current Instructional Practices – Cronbach's Alpha Reliability Analysis

Factor (by Survey Administration)	Cronbach's Alpha Statistics – Scale Reliability Value	
	Usage Statements	Confidence Statements
Start-of-Project Survey		
Overall	0.849	0.935
Provide	0.835	0.911
Guide	0.723	0.861
MID-Project Survey		
Overall	0.801	0.937
Provide	0.827	0.865
Guide	0.363	0.854
POST-Project Survey		
Overall	0.837	0.940
Provide	0.863	0.893
Guide	0.387	0.765



List of Questions:

8. Provide opportunities for students to gather information about problems or issues of importance
9. Provide students with opportunities to explore multiple solution pathways for problems
11. Provide opportunities for students to test their solution pathways
13. Provide students with opportunities to refine and retry a solution pathway
14. Provide opportunities for students to communicate their solution pathways and results to others
15. Provide opportunities for students to take responsibility for the decisions they made about the processes used in solving complex problems

Figure 2: Summary of Results from Current Instructional Practices Survey – Factor Provide – Start to Mid- Project Usage Means for All Teachers

Key features of professional development to support integration of engineering design

Teachers received many layers of support as they embarked on the task of integrating engineering design challenges into math and/or science content classes. Surveys and focus groups were utilized to identify aspects of the professional development teachers felt most helpful in assisting them to integrate engineering design challenges. Teachers answered three surveys during implementation of their units: after the discussion to develop the guiding questions, after the engineering design process (EDP) activity, and after the unit was completed. In this paper results from the surveys for only EDP are presented. The questions were asked using a 4 point scale with 4 = "Strongly Agree", 3 = "Agree", 2 = "Disagree" and 1 = "Strongly Disagree." Specific to our scale, a mean value of 3 or more is desired since that means the respondents, as a group, agreed or strongly agreed with the positive statements in the survey. The standard deviation of a scale indicates the dispersion of the scores compared to the mean. Its absolute value is not good or bad, especially if you want people to have high scores, like we do in this survey. Teachers were overall satisfied with the engineering design process part of the unit (mean of 3.21 out of 4 with a standard deviation of 0.612). As a group, the teachers were satisfied overall with their implementation of the EDP part of the unit. The range of responses for 92.2% of the respondents was either a 3 or 4, satisfied or very satisfied, respectively. This very high percentage level indicates that the teachers were very comfortable and pleased with the EDP aspects of their unit implementation. Teachers were following the desired EDP model outlined by the project. Teachers indicated that they gave their students an opportunity to complete the test-redesign-retest cycle, either in practice or theoretically during their unit. This statement had the highest mean agreement rating (3.48 out of 4 with a standard deviation of 0.642). They also were able to guide their students so that they discovered that there were many possible solutions to the problem of interest (mean of 3.46 out of 4 with a standard deviation of 0.656) and the problems incorporated applications from real life (mean of 3.47 out of 4 with a standard deviation of 0.545). The lowest rated statement was related to the teachers' self-perceived ability to connect their unit to STEM careers (mean of 3.21 out of 4 with a standard deviation of 0.627). This is an identified area of growth for the project and resource team. The results for the EDP closed-ended questions are presented in **Table 3** and once again these confirm that the teachers were pleased with their implementation of the EDP aspects of the unit and reported that these activities supported their making connections with student's real-life experiences and STEM careers.

Student survey responses are used to triangulate teachers' implementation efforts. Ten items on the student feedback survey represented different aspects of the instructional process used in the classroom. These individual statements and the means and corresponding standard deviations for each are presented in **Table 4**. The questions were asked again using a 4 point scale with 4 = "Strongly Agree", 3 = "Agree", 2 = "Disagree" and 1 =g "Strongly Disagree." As stated previously, a mean value of 3 or more is desired since that means the respondents, as a

Table 3: "EDP Questions" – Teacher Survey Responses

Survey Question	All Teachers		
	N	Mean*	Std. Dev.
I was able to relate this engineering design process activity to my students' real-life experiences.	89	3.37	.530
I was able to guide the students so that they discovered that there were many possible solutions to this problem.	90	3.46	.656
I was able to guide the students to define the criteria to be used to select a desirable design solution.	90	3.27	.650
The students understood that the criteria used to select the solution were consistent with real-world limits.	90	3.30	.626
The students were given an opportunity to do through the test-redesign-retest cycle during class - either in practice or theoretically due to limited time or materials.	89	3.48	.642
The engineering design process activity provided examples, and opportunities to show students how this challenge, and its solution, are connected to various STEM careers.	90	3.21	.627
This activity provided examples and opportunities to demonstrate how the engineering design process can be used to solve societal concerns associated with the challenge.	89	3.34	.621
The challenge's solution incorporated applications from real-life into the classroom.	90	3.47	.545

* Scale: 4=Strongly Agree; 3=Agree; 2=Disagree; 1=Strongly Disagree

Table 4: Results from Student Feedback Survey – Instructional Practices Used in the Classroom Factor

Survey Question	N	Mean*	Std. Deviation
This unit related to the real world.	4387	3.33	.688
Solving this challenge can help others, our community, and society.	4403	3.12	.740
I learned about the careers related to this challenge and our solution.	4380	2.98	.813
I received guidance from my teacher when I asked for it.	4413	3.45	.621
I understand how the engineering design process activity allowed us to use the guiding questions to solve the challenge selected.	4406	3.19	.679
I contributed to the group's solution to the challenge.	4401	3.46	.618
Listening to other student's ideas was an important part of the unit.	4399	3.42	.650
There are many solutions to this problem.	4404	3.32	.679
We were able to test our initial solution.	4369	3.30	.709
After our initial test, we were able to think about changes we wanted to make to have a better solution to the challenge.	4400	3.25	.730

* Scale: 4=Strongly Agree; 3=Agree; 2=Disagree; 1=Strongly Disagree

group, agreed or strongly agreed with the positive statements in the survey. For these responses, 95% of the population would fall between the mean plus, or minus two times the standard deviation. For our results, the lower value for the 95% confidence range is lowest for "I learned about the careers related to this challenge and our solution" (at 1.35) and highest for "I contributed to the group's solution to the challenge" (at 2.24). The upper value for all questions

95% confidence range is 4. Therefore, students are using the entire range of the scale to answer these questions which means the scale discriminates between respondents' answers.[5] The overall mean for each question indicated students' level of agreement that their teachers used the instructional processes desired (all means were greater than 3.12 out of 4), as discussed previously in this paragraph, this means that groups of students agreed with the positive statements. Positive student feedback related to their teachers' implementation of the unit included high means for the statements: "I received guidance from my teacher when I asked for it," "I contributed to the group's solution to the challenge," and "listening to other students' ideas was an important part of the unit."

The teacher surveys completed during and after unit implementation provide qualitative data that indicate that engaging in engineering design challenges themselves, as well as repeated opportunities to implement engineering design in their own classrooms, were most helpful in aiding the teachers to adopt this new strategy. For example, in the Teacher Engineering Design Process survey, teachers were asked two open-ended questions: "What supported your ability to guide your students through the engineering design process activity?" and "What helped you implement or made it easier to implement the engineering design process activity?" Answers to the first question focused on what mentorship support was being provided to the participating teachers. Three general categories described the majority of the answers: 1) having completed an EDP activity previously, 2) knowledge of the engineering design process, and 3) access to and help from the resource team. In their answers to the second question, teachers focused on the effects the mentorship had on themselves and their students when they answered this question. Again, there were three categories of answers that the majority of the teachers noted: having done an EDP activity previously; items learned, materials provided and experiences during the summer program; and access to and help from the resource team. Presented in **Table 5** are the categories (or attributes) identified by the teachers in their responses to these two questions and the frequency for each. The most frequently cited answer for both questions is represented by the category: "teachers have gained experience" as a result of creating and implementing multiple units containing engineering design process activities and practicing the engineering design process in summer courses. In this program, teachers take summer courses that expect them to use the engineering design process to solve problems and they implement engineering design process activities at least six times over two school years and thus have multiple opportunities to refine this pedagogy. Notably, for the survey question, "What helped you implement or made it easier to implement the engineering design process activity?", the second most frequent response was the summer program itself, where teachers had the opportunity to engage in engineering design for themselves via the six math and science content courses (three each year).

Of the 2013 courses taken by Cohort 2 teachers, *Engineering Foundations* was the most frequent answer to another open-ended survey question that inquired as to which course was most helpful in terms of implementing desired strategies and pedagogies with their students.

Table 5: Teacher Engineering Design Survey -- What Supported Teachers Implementation of EDP

Thematic Analysis of all Responses	Frequency	Percent
What supported your ability to guide your students through the engineering design implementation activity? (n=105 for total number of comments written, teachers can write no comments or more than one comment)		
Teachers have gained experience	23	22%
EDP & Poster related workshops/seminars	22	21%
All Aspects of the Summer Program	18	17%
Resource Team Support Given During Development, Revision, Implementation, and Review of the Units	16	15%
Technology, Supplies & Materials Provided through the Project	7	7%
Topic or Nature of the Unit Ideas and Activities Supported Implementation	5	5%
Classroom support provided by those other than the Resource Team	4	4%
Comments related to the Characteristics of the Students (such as, engaged, at their knowledge level, interest, behaviors)	3	3%
Unit Structure Provided by the Project	3	3%
Units Contained Hands-On Activities that the Students Could Complete in Class	2	2%
Other Comments	2	2%
What helped you implement or made it easier to implement the engineering design process activity? (n=92 for total number of comments written, teachers can write no comments or more than one comment)		
Teachers have gained experience	26	28%
Comments related to the Characteristics of the Students (such as, engaged, at their knowledge level, interest, behaviors)and Class Size	16	17%
Technology, Supplies & Materials Provided through the Project	15	16%
Resource Team Support Given During Development, Revision, Implementation, and Review of the Units	11	12%
All Aspects of the Summer Program	7	8%
EDP & Poster related workshops/seminars	5	5%
Topic or Nature of the Unit Ideas and Activities Supported Implementation	5	5%
Unit Structure Provided by the Project	4	4%
Units Contained Hands-On Activities that the Students Could Complete in Class	2	2%
Aspects of the Units Included Competition Between Students	1	1%

Engineering Foundations is the seminal course that teacher participants take the first two weeks of the summer program. Teachers learn and apply the engineering design process, as well as are introduced to engineering disciplines and careers and ways that engineering impacts society. However, other summer courses, which explored the integration of engineering into specific disciplines within math and science, were lauded as helpful, especially when teachers had the opportunity to experience productive struggle or become engaged in hands-on learning. Samples of teacher statements regarding the Engineering Foundations course are presented below:

> *I feel that the Engineering Foundations class was the most useful as far as trying to implement the EDP (engineering design process). Just being able to experience the process for myself was helpful. The labs associated with the Engineering Models class were also helpful. I found that being a student again and going through the process of developing and implementing your ideas created a stress that I have not felt in a while.*

This gave me a new appreciation for what my students went through in the lesson. (Cohort 2 Teacher)

I found the Engineering Foundations course the most useful because it helped me practice 'guiding' my students to the solution as opposed to just 'presenting' the answer. The guiding of the student through the process was the critical idea. The math involved they had already learned - they had never used it. (Cohort 2 Teacher)

I found it useful in taking Engineering Foundations because this class allowed us to actually complete projects that taught us the EDP while "doing". I feel I learn best (like the students) when I am able to be hands on. (Cohort 2 Teacher)

During the Summer of 2013, Engineering Foundations was extremely helpful. It provided an opportunity to go through the EDP and experience it firsthand. Other courses, Physical Sciences and Engineering Applications in Math were helpful as we had a project to complete and follow the process as well. (Cohort 2 Teacher)

As mentioned earlier, as part of teacher's second year of the program, they are asked to use their reflections from year one to revise one unit they implemented the previous year and re-teach it during their second year of the program. Through these activities, the teachers are implementing a closed-loop process that parallels the engineering design process to provide continuous improvement for increased student learning. This evidence-based process aids with the reflection process as they consider what to improve in the second iteration. Comments by teachers in an end of year focus group and in the post-unit teacher survey completed after the implementation of each unit supported the conclusion that teachers became more skilled at delivering engineering activities as a result of repeated exposures and experiences, as can be seen from samples of teacher statements below:

The first one [unit taught this year] was so awkward implementing the unit and making sure I did this and did that. After the first one I felt so much more comfortable and when you feel more comfortable with it then you are able to get it across to the kids… I saw that evolve through the different units. Teachers also got more efficient with the process. (Cohort 1 Teacher)

I just taught one of the units I used last year. Last year when I taught it I was so focused on the project, challenge based and STEM and this year I was able to focus on the content that I needed to teach and that they understood all that they needed to -- Both the math piece and the project piece. I also wasn't afraid to jump in with another math lesson in the middle of doing the project just so they could really be confident with the math. (Cohort 1 Teacher)

Just as engineers do not always find the optimal solution after the first iteration, teacher participants find that multiple opportunities to practice and implement the engineering design process improve their delivery of content. Both by practicing the engineering design process themselves over the summer and having multiple chances to incorporate engineering design in K-12 classrooms, their confidence level with the process seemed to increase, as also indicated by the mid-project current instructional practices survey results. These results were previously shown in **Figures 2**. As a result, one can surmise that time and experience were key factors in this professional development program.

Another important factor was the support received from resource team coaches or mentors, as well as doctoral Fellows in engineering assigned to assist in the classroom. In teacher surveys, the other top response to the two questions mentioned above was the support of the resource team coaches. This theme was also evident in end of summer evaluations and in end of the year focus groups. Samples of teacher statements are presented below:

> *I loved my RT (resource team) members – so helpful – "real live engineers" will be here tomorrow, I would tell the kids. … Share ideas with real actual engineers, kids looked forward to that.* (Cohort 2 Teacher)
>
> *Super valuable to have them (resource team coaches). We get evaluated all year long by our administrators… and to have somebody in the classroom that is literally there to help us and encourage us, which meant a lot. There is a lot of negative stuff and I think stressful pieces. And to have the mentor come in and help out and just be in your corner with the (program's) intensive work load, the encouragement was great. I will continue to be in touch because they have become not just (program) mentors but also career mentors.* (Cohort 1 Teacher)
>
> *I could not have done it without my mentors.* (Cohort 1 Teacher)
>
> *I had a great team; I liked them coming in, critiquing. They got along well with the kids … the kids asked for them.* (Cohort 2 Teacher)

As part of the evaluation process, resource team members complete logs when interacting with teachers. These logs are completed on a regular basis by the resource team members via an on-line survey with both close-ended and open-ended questions that allow them to quickly summarize their interactions; in fact, entire email conversations can be cut and pasted into a text box to summarize the interaction. While these logs are likely underreported, resource team members completed 413 logs during the 2013-2014 school year representing interactions with all teachers. A summary of the nature of the communication for these logs are shown in **Table 6**. While these data are still being analyzed and triangulated with the teacher data received, 41% of these logs were related to unit implementation.

In post-unit surveys, teachers are asked the close-ended question: "What support did you receive from the University?" Of the 73 answers to this particular survey question, 64 (88%) indicated "resource team support in the development of unit"—the most frequently selected

Table 6: Resource Team Member Communication Log: Nature of the Communications

Nature of Communication	Frequency	Percent
Unit/Lesson/Activity implementation	169	41%
Other (majority are related to classroom observation)	101	25%
Planning related to a site visit	100	24%
Engineering-design-based aspects of the lessons	44	11%
Challenge-based aspects of the lessons	39	10%
Content support	39	10%
Administrative needs	37	9%
Unit/Lesson/Activity development	38	9%
Advice related to a specific activity	31	8%
Advice related to pedagogy	26	6%
Video Development	14	3%
Planning related to a teacher-led professional development	9	2%
Coordinate communication among teachers	5	1%
Technology Integration	3	1%
Unit topic selection/identification	2	0%

N=657 (some logs related to more than one category)

answer to this question. Of the remaining nine responses, three did not answer the question, five answers reveal that this unit was re-taught or adapted from another teacher and therefore very little outside help was needed, and one indicated that a faculty member from one course provided him with the idea for the unit. Below is a sampling of answers to the question regarding resource team support:

> *One resource team member provided feedback on the part of my unit where students would decide which group member's product re-design idea they should go with. Rather than make an arbitrary vote, this team member helped me to come up with a rubric so the team could make a more objective decision, which models after the actual engineering process.* (Cohort 1 Teacher)

> *The resource team members let me brainstorm and bounce ideas off of them. For example, Debbie had the idea to connect my slide lesson with the Science teacher's forces of motion lesson and design a whole playground together. Rob was very good and keeping my ideas within a reasonable time frame. Lori asked me to consider my grouping options. A doctorate candidate showed me how to use an accelerometer which would be helpful with movement graphing.* (Cohort 2 Teacher)

> *They gave me a new term called "productive struggle" to use and think about when determining how much assistance to give students that are solving a problem.* (Cohort 1 Teacher)

> *The resource team came into the classroom and helped students design and redesign their water turbine blades. The resource team also helped students isolate one variable*

for testing. The resource team members also helped me limit the number of variables during the student testing portion of my lesson. (Cohort 2 Teacher)

They helped me with unit plan design and critiqued activities. They suggested individuals with expertise that I could get advice from. They made suggestions about assessments. (Cohort 1 Teacher)

The resource team really encouraged me to practice making hand warmers myself prior to giving the heat sealer to the students. This was very beneficial. The resource team also helped me think about the ACS (real world applications, career connections, and societal impact) and be sure to incorporate this into the unit pertaining to the designing the labels with warnings on them. (Cohort 2 Teacher)

They helped me in the design of the shake table that I built. I was going to make a part that caused the shake table to move in the vertical plane, but the team advised against that because real earthquakes do not move manmade structures very much in that direction. (Cohort 1 Teacher)

The resource team is extremely helpful. David has gone above and beyond as a coach and has helped in many ways. He comes to my school regularly to help where needed to show students new and different ideas that can help them with their projects. (Cohort 1 Teacher)

The resource team helped me implement time management solutions for my students (my biggest challenge). They also provided me with some specific resources regarding recycling practices in (our city). Most important, they provided in class support while individual student groups were working on the challenge. This is nearly impossible to do alone when each team has a unique approach to the challenge. (Cohort 2 Teacher)

My resource team gave me input on how to keep students on track. They suggested that I have students keep an engineering journal to jot down any changes they make on their cars. (Cohort 2 Teacher)

They helped me while implementing the lesson to help each individual group get the help that they needed to do the math involved in the unit. (Cohort 2 Teacher)

They helped me narrow down the large amount of concepts that I was originally considering when developing this unit. They also helped me look at materials to use during the building of the catapult. (Cohort 2 Teacher)

Resource team members helped me develop the challenge for the unit. I really wanted to (do) food preservation, but I was not sure how create a challenge. They also helped me decide how to test the designs. (Cohort 2 Teacher)

They helped me put more investigation on the students than simply giving the formulas to them. (Cohort 2 Teacher)

As demonstrated by the variety of responses in this sampling, the resource team and Fellows serve many functions to the teachers. They assist in the classroom while student groups are engaged in engineering design activities. They assist with unit development. They recommend materials for the engineering challenges. They help teachers refine the challenge and constraints. They advise in terms of pedagogy. They ensure that engineering challenges for students are grounded in real world applications, as well as serving a host of other functions.

Impact of engineering design challenges on students

The program invests much time and effort into training math and science teachers to incorporate engineering design challenges (real-world applications) into their content classes. While this may be enjoyable and engaging to students and provide some awareness in terms of engineering career options and societal impacts, does this practice hinder or aid student acquisition of content?

While this program does not yet have an effective control group by which to measure student academic performance, all participating teachers pre-assess students' academic content knowledge prior to the start of a unit and then re-assess students' knowledge of the same content following the completion of the unit. Looking at samples of paired t-tests with significance determined with two-tails, 70 out of 76 units had a significant increase in scores from the pre-test to the post-test at a 95% confidence interval. An effect size of 0.76 was calculated for all pre-post assessment results combined. While this effect size is very large, it was expected since the assessments were created specifically for each unit. This suggests that content was successfully acquired despite an alternate method of instruction. Individual teacher testimonials also support the need for a shift towards an incorporation of engineering design challenges as a way to solidify content in such a way that the students can see a purpose for learning throughout the learning process – from beginning to end. Consider the comments and experience of a Cohort 2 math teacher who used engineering design process to teach fractals:

To pass a quarter I require my students to pass a minimum number of tests or projects by 80%. I do this to motivate my students to acquire depth in at least a few areas of math, instead of just getting by with a 60% average, which is not uncommon among adolescents.

It is not unusual in my classroom culture for students to come in after school to re-take a test to acquire the minimum requirements for passage, even though they have the minimum 60% for passage.

It had occurred to me that significantly fewer students came in that quarter to retake the fractals test than other tests. A greater population had reached the 80% threshold on that test, than other tests that quarter.

Subjectively that could be attributed to at least two attributes of CBL (Challenge Based Learning). One is the repetitive nature of the EDP (Engineering Design Process). It was the first time I have lead the students to redesign a project and do it again. In the video testimonies I noticed that the kids talked about, unsolicited from me, that at first they didn't understand, but then when they did it again there was an epiphany.

The other possibility was that they bought into the project. I noticed that they liked the freedom of designing within parameters. They also liked learning and improving upon their teacher's exemplar at the beginning. (I reported at the beginning of the project that I made the mistake of building my fractal antenna from the outside in. Not one student team repeated my mistake). They also liked improving on their own designs the second time around.

They had the same experience with the math. I believe that it was important that the groups who chose more complex designs and therefore more difficult math were complimented for taking the risk, in spite of the fact that they had more failures than those who chose easier designs.

One requirement of participating teachers is each one presents four professional development (PD) sessions to their peers over two years (two per year). One way to fulfill the PD requirement is to provide one-on-one mentoring to another teacher not participating in the program. As a result, a non-participant teacher has the opportunity to observe a program participant's implementation of an engineering design challenge and then is given the opportunity to initiate the same challenge in his or her own classroom. The experience emphasizes the changes all teachers need to make in response to the new state assessments and teacher evaluation system. Input received from one such non-participating science teacher is presented below:

Having been through the entire OTES (Ohio Teacher Evaluation System) */ eTPES* (Ohio Teacher and Principal Evaluation Systems) *process last year and into this year, I kind of have an edge on what it takes to achieve the rating of Accomplished on the Teacher Performance Evaluation Rubric. The more STEM, Inquiry, and Challenge-Based Learning projects we can incorporate in our classrooms, the more, we as science teachers, are on our way to achieving the highest rating in our state. And when teachers finally get a load of what the 2014 8th Grade Science Assessment(s) look like, it will finally become crystal clear. Teachers have to change the way they teach Science. This PD project that Paul (program participant) and I are working on is spot-on what teachers need...and more of it!*

More study is needed to determine whether teaching using engineering design challenges results in superior content acquisition as compared to teaching using traditional methods. In addition to acquiring content knowledge, teachers reported in focus groups that students were positively impacted by the shift in instructional strategies:

> *Higher student engagement and the challenges also provided a healthy academic competition that some students really thrived on.* (Cohort 1 Teacher)

> *Overall learning is higher, covering all kinds. Students are more likely to take academic risks and think better on their own.* (Cohort 1 Teacher)

> *Students' learning curve increased greatly compared to the way I used to teach. Students work together and implement things.* (Cohort 2 Teacher)

> *With usual lessons, wrong is wrong. With the engineering design process, failure is actually a good thing. They [students] learn something that didn't work so they can go back and redesign.* (Cohort 2 Teacher)

Conclusions and recommendations for future study

In order to have a longer term impact, this program focuses on changing instructional practices of secondary math and science teachers, who will in turn impact thousands of students over the course of their careers. Participating teachers practice and implement engineering design challenges over two years. Witnessing the positive impact of these challenges on students' content acquisition and engagement level serves as motivation to continue these practices even after formal participation in the program is complete. Based on project data, teachers attribute their ability to successfully implement engineering challenges to 1) summer program classes and experiences that allowed them the opportunity to engage in the engineering design process for themselves; 2) multiple practicing opportunities in implementing engineering design in the classroom, as the program requires participants to execute five units featuring engineering activities over two school years; and 3) the continual support of the resource team. Qualitative teacher comments and observations are backed by student pre and post assessment results citing student improvement in content knowledge as a result of using engineering design challenges as a vehicle for learning. More studies are needed to compare student performance using engineering design challenges versus a more teacher-directed approach. As the state of Ohio moves to more performance-based assessment starting this school year (2014-2015), this comparison will become even more relevant. In order to sustain the program, the project team will need to pinpoint exact factors and degree of treatment needed to change teachers' instructional practices. For example, as the grant expires and the project team examines ways to sustain the efforts, could a smaller scale teacher training program be developed that yields the same degree of effectiveness?

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Bibliography

1. Capobianco, B. A. (2013). Learning and teaching science through engineering design: Insights and implications for professional development. Association for Science Teacher Education, January, Charleston, SC.
2. Common Core State Standards Initiative. (2014). Retrieved from http://www.corestandards.org/
3. Doerr, H. M., Goldsmith, L. T., & Lewis, C. C. (2010). Mathematics professional development. National Council of Teachers of Mathematics, Professional Development Research Brief, November 19. Retrieved from http://www.nctm.org/uploadedFiles/Research_News_and_Advocacy/Research/Clips_and_Briefs/Research_brief_15-Goldsmith%281%29.pdf.
4. Fortus, D., Dershimer, R., Krajcik, J., Marx, R., & Mamlok-Naaman, R. (2004). Design-based science and student learning. Journal of Research in Science Teaching, 41(10), 1081; 1081-1110; 1110.
5. George, D. & Mallery P. (2003). SPSS for Windows step by step: A simple guide and reference. 11.0 update (4th ed.). Boston: Allyn & Bacon.
6. Gliem, J.A. & Gliem, R.R. (2003). "Calculating, Interpreting, and Reporting Cronbach's Alpha Reliability Coefficient for Likert-Type Scales. Presented at the 2003 Midwest Research-to-Practice Conference in Adult, Continuing, and Community Education, The Ohio State University, Columbus, OH, October 8-10, 2003.
7. Guskey, T. R. (2000). Evaluating professional development. Thousand Oaks, CA: Corwin Press, Inc.
8. Guzey, S. S., Tank, K., & Wang, H. (2014). A high-quality professional development for teachers of grades 3-6 for implementing engineering into classrooms. School Science and Mathematics, 114(3), 139-149. doi:10.1111/ssm.12061.
9. Heck, D., Banilower, E., Weiss, I., & Rosenberg, S. (2008). Studying the effects of professional development: The case of the NSF's local systemic change through teacher enhancement initiative. Journal for Research in Mathematics Education, 39(2), 113-152.
10. Mehalik, M. M., Doppelt, Y., & Schuun, C. D. (2008). Middle-school science through design-based learning versus scripted inquiry: Better overall science concept learning and equity gap reduction. Journal of Engineering Education, 97(1), 71-85. doi:10.1002/j.2168-9830.2008.tb00955.x
11. National Academy of Engineering. (2010). Standards for K-12 engineering education. Washington, DC: National Academies Press.
12. NGSS Lead States. (2013). Next generation science standards: For states, by states. Retrieved from http://www.nextgenscience.org/.

13. Ohio Department of Education. (2011). Ohio's new learning standards: Science standards. Retrieved from http://education.ohio.gov/Topics/Ohio-s-New-Learning-Standards/Science.

14. Schwartz, D. L., Lin, X., Brophy, S., and Bransford, J. D. (1999). Towards the development of flexibly adaptive instructional design," In C. M. Reigeluth (Ed.), Instructional-Design Theories and Models: A New Paradigm of Instructional Theory, Vol. 2, pp. 183-213. Mahwah, NJ: Erlbaum.

15. Schwartz, D. L., Lin, X., Brophy, S., & Bransford, J. D. (1999). Toward the development of flexibly adaptive instructional designs, In C. Riegliuth (Ed.), Instructional Design Theories and Models, Vol. 2, pp. 183-213. Hillsdale, NJ: Lawrence Erlbaum Associates.

16. Walker, J. H., & Bird, M. (2000). Amodel of professional development for allied health professionals who are clinical teachers. ANZAME: The Association of Health Professional Education Annual Conference Papers and Abstracts, 2-5 July, Fremantle, pp. 55-60 (ISBN 1 86308 081 3).